Uncertainty DRI
Adaptive Rapid Environmental Assessment

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LONG-TERM GOAL

Development and operational implementation of a new tactical tool for real-time assessment of the spatial and temporal statistics of the littoral acoustic environment, which is optimal in the context of sonar performance within the constraints of the deployable in-situ measurement resources.

OBJECTIVES

The objective of the AREA research is to develop a probabilistic methodology for optimal, in-situ assessment of the environmental parameters most critical to the uncertainty of the acoustic prediction, within constraints of the actual acoustic system configuration and the available tactical REA resources. The goal is an efficient modeling and simulation framework, which allows for real-time prediction of the reduction in sonar performance uncertainty associated with specific deployment strategies for the REA resources. Specific scientific objectives include a fundamental understanding of the relative significance of individual environmental parameters to performance of a specific sonar system and based on this understanding defining optimal parameterizations of the environmental parameters. Another crucial component is the classification of the limiting spatial and temporal scales, below which the in-situ sampling resources are totally inadequate and the uncertainty remains stochastic.

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Development and operational implementation of a new tactical tool for real-time assessment of the spatial and temporal statistics of the littoral acoustic environment, which is optimal in the context of sonar performance within the constraints of the deployable in-situ measurement resources.

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APPROACH

Uncertainty propagates through the complete chain for sonar performance: environment, acoustics, processing, and operator. In regard so, the development of AREA is a close coupling of ocenography, geology, geophysics, acoustics, and signal processing, while being aware of the needs of the end user. It will be developed through a series of Observation System Simulation Experiments (OSSEs) [1] carried out in close collaboration with the two DRI partner teams, led by Allan Robinson (HU) and Charles Holland (PSU). The OSSEs will initially be based on the 1996 Shelf Break Primer experiment which had a strong oceanographic forecasting and acoustic components [2].

The center piece of the AREA concept is the optimal combination of classical environmental assessment based on databases and local measurements, and full-blown forecasting frameworks based on modeling and assimilation with adaptive in-situ sampling. The two partner teams provide the AREA team with their forecasts of the coupled PDFs for the seismo-acoustic parameter fields, and the associated spatial and temporal scales. The AREA team uses the ocean acoustic modeling and sonar processing frameworks to transform these into PDFs directly representing the associated effect on specific sonar performance metrics. Those performance forecasts are then used to identify optimal deployment patterns for the in-situ sampling resources such as XBT, CTD casts and AUV surveys. After the REA measurements have beem collected, they are fed back to both parter teams to update their environmental forecasts, which again pass through the sonar modeling framework, producing sonar performance predictions with sharper uncertainty.

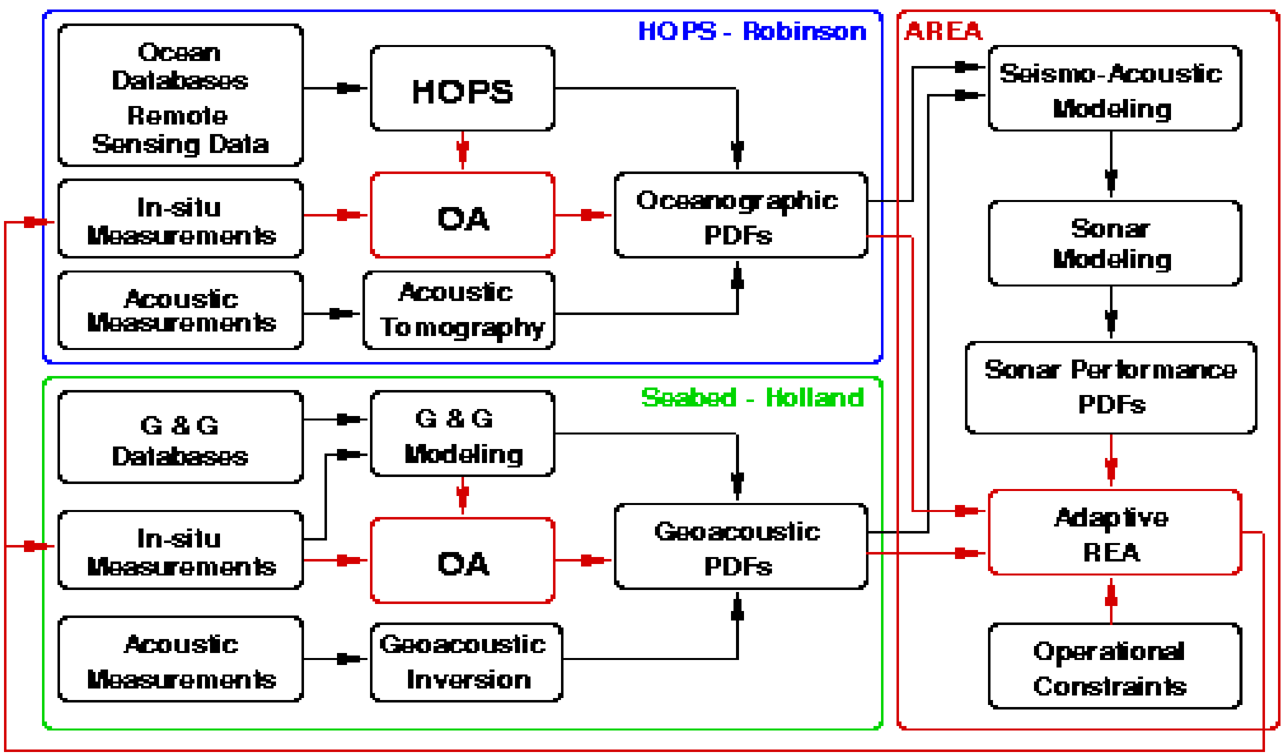


Figure 1: Adaptive Rapid Environmental Assessment system wiring diagram

The research effort is centered around the ocean acoustic modeling and sonar processing frameworks developed and maintained by the MIT ocean acoustics group [3, 4]. The sonar performance uncertainty associated with the oceanographic variability is most conveniently determined using Monte-Carlo simulations of the sonar response for random realizations of the oceanographic statistics predicted by the forecasting framework. In regard to the seabed variability, the OASES seismo-acoustic modeling framework [3] can be used to determine the sonar uncertainty associated with uncertainty from both large-scale deterministic variability and small-scale seabed roughness and volume inhomogeneities. Sonar performance metrics are easily built within the information theory framework, for example, using the Fisher Information Matrix (FIM), which specifies the asymptotic limit in mean-square estimation error and directly quantifies the parameter couplings [5, 6]. The FIM can be used together with an acoustic modeling framework to define an optimally uncoupled, or System-Orthogonal Acoustic Parameterization (SOAP), thus making it possible to identify the most significant environmental features observable in system response. Finally, to determine an optimal deployment of the REA resources it will be necessary to determine a Measure of Effectiveness (MOE) for each combination of critical environmental parameter, REA resource, and deployment pattern. These MOEs must be combined with a cost model to define a quantitative cost-effectiveness model for each resource/parameter combination. The development and validation of those models are major objectives of the AREA research effort.

WORK COMPLETED

A major component of the FY02 is the investigation of the effect of the environmental uncertainty to sonar performance prediction. This is done in the context of matched-field processing for passive source localization using a vertical receiving array [7]. The initial investigation is on a shallow water environment off the coast of San Diego from the Shallow Water Evaluation Cell Experiments (SWellEX) [8], and later this same approach is applied to the Shelfbreak Primer Experiment site, south of New England in the Middle Atlantic Bight [2]. Monte Carlo simulations are used to investigate the relative significance of individual environmental parameters to matched-field performance including peak mainlobe-to-sidelobe ratio and mainlobe peak displacement in matched-field ambiguity output. The effect of adding uncertain environmental variables to source localization performance is also quantitatively investigated in terms of parameter coupling using parameter estimation mean-square error bounds.

On the acoustic parameterization side, the bulk of the effort in FY02 has focused on developing system-optimal representation for sound velocity variation in the water column, a dominating acoustic uncertainty factor due to oceanographic uncertainty. This has led to a new set of orthorgonal basis for sound velocity representation in both range-independent and weakly range-dependent environments. Compared to the traditional Empirical Orthogonal Functions (EOFs), the expansion coefficients on this new basis are decoupled in terms of system response.

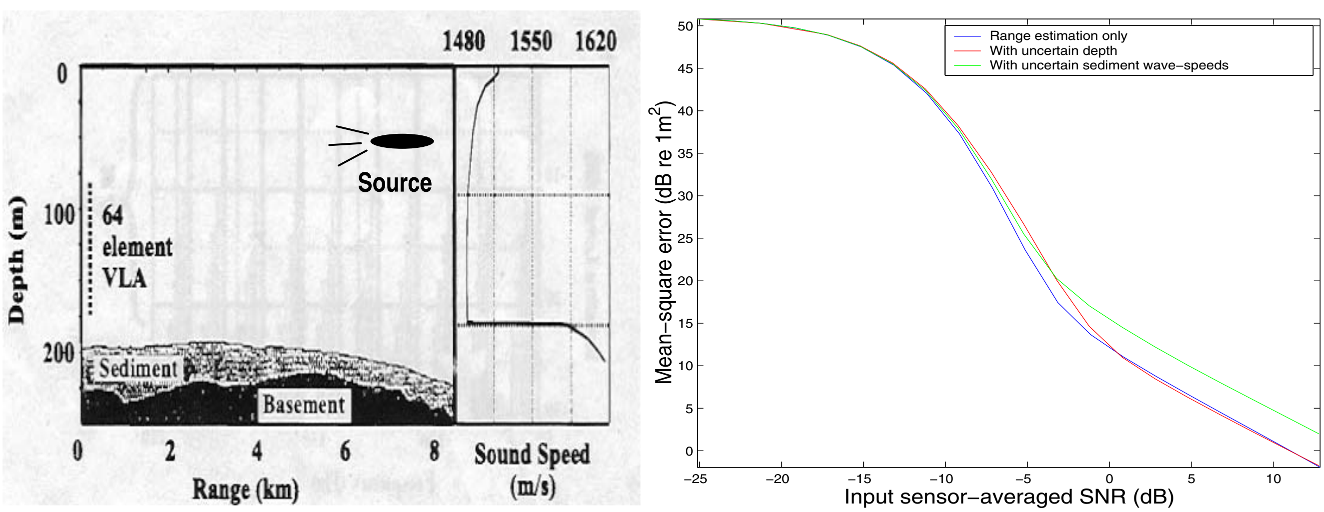
Besides, considering the significance of surface reverberation to shallow water acoustical uncertainty and its relatively lack of modeling effort, the influence of a 3D surface wave has been examined.

RESULTS

Effects of Environmental Uncertainty to Sonar Performance Prediction

Matched-field methods concern estimation of source locations and/or ocean environmental parameters by exploiting full wave modeling of acoustic waveguide propagation. Because of that, they have achieved performance improvements over the traditional plane wave beamforming methods, but also shown a strong sensitivity to environmental mismatch [7]. Hence they fit very well in the framework of the Uncertainty DRI.

The sonar performance modeling work of Xu [4] has shown that performance of matched-field methods demonstrates several operation regions in regard to the signal-to-noise ratio (SNR) (see, for example, Fig. 2(b)). At high SNR, the error in source localization is small and local around the true position; below some threshold SNR, estimates are subject to global ambiguities due to the nonlinear parameter-dependence of the signal field, leading to a significantly increased location error; at very low SNR, estimation is dominated by noise and the error is completely determined by *a priori* information of the source location. In the presence of environmental/system mismatch, estimates can be seriously biased, showing an almost "flat" mean-square error at high SNR. The threshold SNR and the bias are determined by the peak mainlobe-to-sidelobe ratio (PMSR) and the mainlobe peak shift (MPS) in the matched-field ambiguity output. Based on those results, Monte Carlo simulations have been applied to scenarioes in both Shallow Water Evaluation Cell Experiments (SWellEX) (Fig. 2(a)) and Shelfbreak Primer Experiments, showing the statistics of PMSR and MPS under the given environmental uncertainty. The set of environmental parameters critical to matched-field performance prediction varies from scenario to scenario and is strongly dependent on environmental parametrization [9]. Particularly the parameter coupling from the underlying physics complicates such investigation.



(a) *(b)*

Figure 2: Passive source localization by matched-field processing: (a) example environment and system configuration from the Shallow Water Evaluation Cell Experiments [8]; (b) mean-square error as a function of SNR in source range estimation specified by the Ziv-Zakai bound [4].

In Bayesian framework, environmental parameters are modeled as random quantities, subject to the given uncertainty, estimated together with source parameters. The effect of adding additional parameter to source localization depends on parameter coupling. As shown in Fig. 2(b), adding a strongly coupled parameter (e.g., sediment wavespeed) degrades the asymptotic (high SNR) performance of source range estimation due to the added mainlobe ambiguity but the sidelobe threshold is often not increased; adding a weakly-coupled parameter (e.g., source depth) does not degrade the asymptotic performance but could increase the threshold SNR due to the added sidelobe ambiguity. This provides an important guideline for predicting sonar performance in the presence of environmental uncertainty.

System-Orthogonal Acoustic Parameterization

To limit the degrees of freedom ocean parameters are often represented in terms of Empirical Orthogonal Functions (EOFs). In the water column the EOFs are derived from direct measurements of sound velocity profile (SVP) and they are orthogonal in regard to the statistics of the SVP variations [10]. Viewed from the sonar output end, however, the effect of an error in one EOF is usually coupled with the effect of the error in another. Thus the relative significance of the individual EOFs cannot be directly determined.

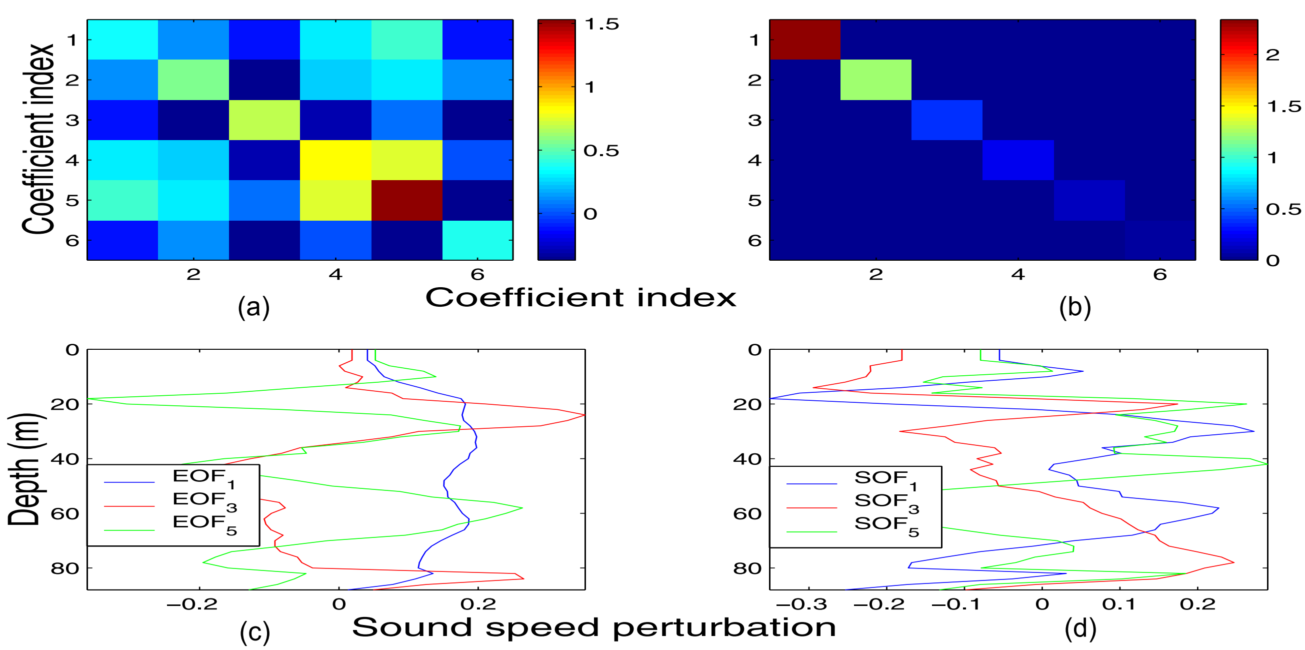


Figure 3: Parameterization for sound velocity perturbation: (a) CRB matrix for the first six EOF coefficients; (b) CRB matrix for the corresponding SOF coefficients; (c) example EOFs; and (d) example SOFs.

The Cramer-Rao bound (CRB) matrix directly quantifies the parameter coupling and thus can be used together with an acoustic modeling framework to define a system-orthogonal acoustic parameterization. Denote r as source range and $\underline{g}$ as the expansion coefficients of the SVP variation

using a set of L arbitrary orthogonal (distribution) functions. The CRB matrix can then be divided as individual error terms for both r and $\underline{g}$ and their coupling:

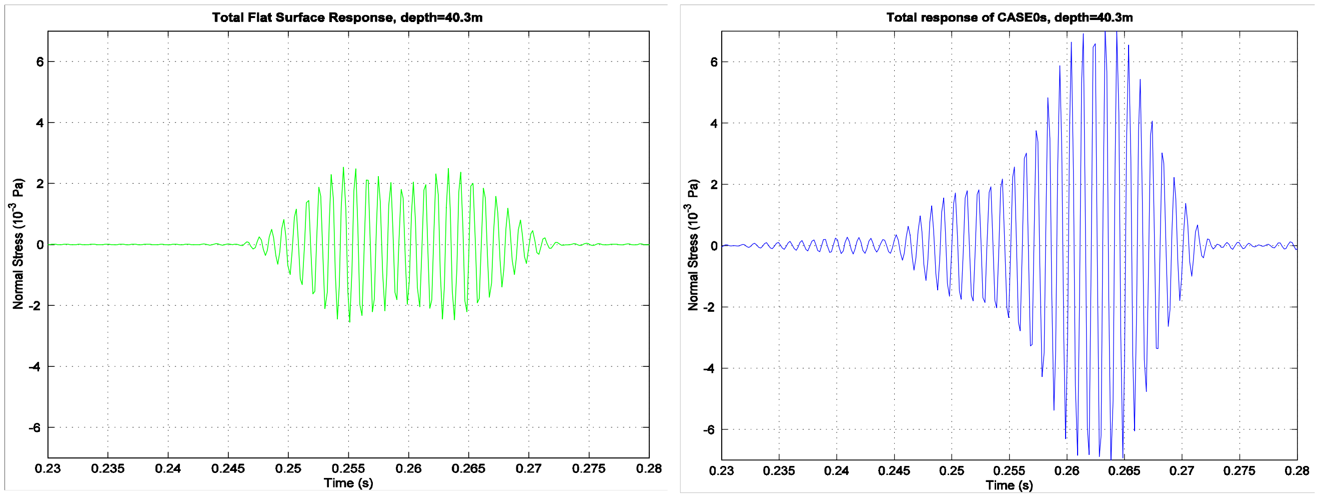
$$\begin{bmatrix} CRB^{r}_{1\times1} & CRB^{r\underline{g}}_{1\times L} \\ CRB^{\underline{g}r}_{L\times1} & CRB^{\underline{g}\underline{g}}_{L\times L} \end{bmatrix}$$

A diagonal $CRB^{\underline{g}\underline{g}}_{L\times L}$ states that errors in the estimation of individual SVP coefficients are uncoupled. A set of such orthogonal functions has been derived for range-independent or weakly range-dependent environments [11], using the perturbation approach in Ref. [12]. Fig. 3 shows an example application in an ideal waveguide with SVP statistics from the 1996 Shelfbreak Primer Experiment [13]. Clearly EOF coefficients show some mutual coupling while the coefficients of the derived system-orthogonal functions (SOFs) are completely decoupled. EOF_5 is now the major source in estimation uncertainty, which is captured by SOFs (comparing SOF_1 to EOF_5).

It is interesting to note that to reduce the uncertainty in source localization by reducing environmental uncertainty, it is desired to have a strong coupling between source parameters and environmental parameters, i.e., $CRB^{gr} \to \underline{1}$. On the other hand, to have a robust source localization algorithm, one would have $CRB^{gr} \to \underline{0}$. Those are the target of continued research effort.

3D Wavy Surface Reverberation Modeling

In typical wave conditions, the sea waves add position uncertainties of several meters as compared to the situation with a flat surface and the added uncertainty is stochastic in nature. The state-of-the-art of simulating 3D surface wave forms developed at MIT is quite advanced. It takes advantage of the computing speed of 2D FFT's and then synthesize the 3D sample functions from high resolution 2D waves at a few angles. Currently examined (Fig. 4) is the influence of a realistic, but fixed, surface wave shape on reverberation from the surface (wind-speed = 15 m/s and Pierson-Moskowitz spectrum with $\cos^4$ spreading function). Note that the later arrivals show a coherent scattering from the wavy surface. Although we are able to simulate the time-evolution of surface shapes, including the major effect of the dispersion of the sea waves, we do not yet have the acoustic scattering tools to efficiently evaluate the influence of this time evolution. It is important to develop these tools because the convecting and evolving complicated wave pattern influences the Doppler shift of the acoustic waves. When we have the necessary tools, by acoustically measuring the sea surface statistics, we will be able to use the Doppler shifts to aid in target localization.



(a) (b)

Figure 4: Received signal time series in a shallow water waveguide:
(a) flat surface; (b) 3D wavy surface.

IMPACT/APPLICATION

The long-term impact of this effort is the development and operational implementation of a new tactical tool for real-time assessment of the littoral environment. Specifically, the AREA concept improves sonar performance prediction by capturing and then mitigating dominant environmental uncertainty under operational constraints, which takes optimum advantage of combining both oceanographic forecasting and sonar performance prediction components as well as the mobility, autonomy and adaptiveness of the REA resources. For example, the System-Orthogonal Acoustic Parametrization being developed provides a framework to connect oceanographic parametrization to sonar modeling as well as potentially to end user modeling.

TRANSITIONS

A joint experiment with SACLANTCEN/HOPS is being planned, which includes HOPS nested forecasting, MFP experiment, real time adaptive rapid environmental assessment with AOSN. The AREA concept will then be tested and integrated to GOATS (Generic Ocean Array Technology Sonar) effort [14].

The OASES environmental acoustic modeling code continues to be maintained and expanded. It is continuously being exported or downloaded from the OASES web site (http://acoustics.mit.edu/arctic0/henrik/www/oases.html), and used extensively by the community as a reference model for ocean seismo acoustics in general.

RELATED PROJECTS

This effort is part of the Uncertainty DRI. In terms of environmental input and forecasting, it is strongly related to two other DRI partner projects: HOPS (PI: A. Robinson) and SEABED (PI: C. Holland).

Regarding its REA resource deployment and experimental test, there are strong connections to the GOATS Joint Research Program conducted by SACLANTCEN and MIT with ONR support (Grant # N00014-97-1-0202).

The OASES modeling framework being maintained and upgraded under this contract is being used intensively as part of the GOATS effort, aimed to developing environmentally adaptive bi- and multi-static sonar concepts for autonomous underwater vehicle networks for detection and classification of proud and buried targets in very shallow water.

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